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ASSESSMENT OF SIMULTANEOUS USE OF NO_x CONTROL SYSTEMS ON STATIONARY SOURCES IN CALIFORNIA

VOLUME I: EXECUTIVE SUMMARY

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ABSTRACT

The costs and performance potential were assessed for the simultaneous use of NO_x control systems applied in various combinations and at various control levels on 11 stationary sources. NO_x control systems which were studied included combinations of low NO_x burners (LNB), selective non-catalytic reduction (SNCR), and selective catalytic reduction (SCR). The stationary sources, totalling 11 different installations, include refinery process heaters and industrial boilers of various sizes and types, a carbon monoxide boiler, and a glass melting furnace.

Primary emphasis was on NO_x reduction costs and corresponding applicability of various control strategies as applied to major emission sources for a range of sizes and equipment operating conditions. In addition, the cumulative performance potential of each combination control option was assessed.

It was concluded that generally the applicability of a combination of NO_x controls is feasible, but the cost-effectiveness is unique for each unit examined. In addition, overall system complexity increases as denitrification systems are added. However, some general trends were detected: 1) application of NO_x controls to refinery heaters is, on the average, less costly than for industrial boilers; 2) application to larger units is, on the average, less costly than for smaller units; 3) the combination of LNB + SCR is generally competitive with SCR at control levels between 80% to 90% NO_x reduction; 4) from 70% to 90% reduction, SCR is usually more cost-effective; 5) at 70% NO_x removal LNB + SNCR is more attractive; and 6) at 50% and 40% NO_x reduction, SNCR and LNB, respectively, have the lowest cost.

Capital investment cost estimates are provided in mid-1981 dollars and reflect estimated retrofit complexity factors for the various installations. Annual control costs in terms of dollars per pound NO_x removed and dollars per million Btu thermal input are also reported.

ACKNOWLEDGEMENTS

Contributions were made to the study in the form of data and information by numerous individuals and organizations to whom appreciation is gratefully extended. However, assembly of the data, assessments, and conclusions drawn are those of the authors. The assistance and guidance of members of the California Air Resources Board staff, especially the Project Officer, Mr. Jack Paskind, Manager, Emissions Control Technology Research Section, as well as Mr. Manjit Ahuja, Air Resources Engineer, are acknowledged.

Contributions in the form of operating information and site data were provided by operators of the refinery equipment and industrial boilers.

Information on control systems and applications was provided by Joy Industrial Equipment Company, the John Zink Company, Coen Company, Inc., the Forney Engineering Company and the Gas Research Institute..

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CONTENTS

GLOSSARY

LNB	low NO_x burner
SNCR	selective non-catalytic reduction also referenced in the literature as Thermal $DeNO_x$ as patented by Exxon Research and Engineering Company
SCR	selective catalytic reduction
CARB	California Air Resources Board
CO	carbon monoxide
NO_x	oxides of nitrogen (NO and NO_2)
MMBtu	million British thermal units
^oC	degrees Celsius
^oF	degrees Farenheit
NH_3	ammonia
NH_4HSO_4	ammonium bisulfate
SO_2	sulfur dioxide
SO_3	sulfur trioxide
MW_e	megaWatt electrical equivalent
\$/lb	dollars per pound
SCFM	standard cubic feet per minute
ACFM	actual cubic feet per minute
CFH	cubic feet per hour
nM^3	normal cubic meters
O&M	operating and maintenance
ppm	parts per million
FCC	fluid catalytic cracker

1.0 INTRODUCTION AND SUMMARY OF FINDINGS

1.1 Scope of Study

The objective of this study was to determine the applicability, performance potential and cost of various methods of NO_x control to a variety of stationary sources representing a range of refinery heaters and boilers, industrial boilers and a glass melting furnace. Low NO_x burners (LNB), selective non-catalytic reduction (SNCR), also designated as thermal $DeNO_x$, and selective catalytic reduction (SCR) were the three methods considered. The stationary sources selected for the study were based on stationary source and size guidelines provided by the Research Staff, California Air Resources Board (CARB). Control strategies included employing each method alone and in combination with the others.

Information was obtained from the operators of the various stationary equipments. Information on control system characteristics was obtained by recent discussions with various developers, suppliers and users of the hardware and also drew heavily on the detailed survey conducted by The Aerospace Corporation and reported in Reference 1-1.

The analysis was based on the stationary sources operating at normal or observed load. In some cases extrapolations were extended to design load, 75% of design load, or 50% of design load. Similarly, cost-effectiveness estimates ($/lb NO_x removed) were determined for design conditions and adjusted for observed or expected operating load. In addition to the effect of load on cost-effectiveness, the effect of exhaust gas reheat (where required for SCR catalyst operation) and a comparison of control costs of gas versus oil fuels were made.

1.2 Description of Sources

The stationary sources included five refinery heaters rated from 65 to 435 MMBtu/hr, five industrial boilers rated from 4 to 336 MMBtu/hr, one CO boiler rated at 275,000 lb/hr steam, and one 200 ton per day container (flint) glass furnace. Table 1-1 is a summary of the stationary sources and their respective emission characteristics based on the use of primarily gaseous fuels which are currently in use and considered in the study guidelines to be in continued use in the future.. Because of the diversity of heater and boiler designs and sizes that are located in the Los Angeles Basin, it cannot be stated that any of the equipment studied can be considered "typical". However, an attempt was made to encompass the range of equipment sizes and determine cost trends, if any, based on this parameter. In that sense it is believed the resultant evaluation is representative of the control costs that could be incurred based on the trends developed in the study.

1.3 Description of Technology

The technology for combined NO_x controls was based on individual technology operating experience in U.S. and Japan (References 1-1 and 1-2). Desired technical performance is generally achievable given required space and configurations.

TABLE 1-1

NO_x EMISSION CHARACTERISTICS OF STATIONARY SOURCES BURNING GASEOUS FUELS

EQUIPMENT	SIZE, MMBtu/HR	UNIT DESIG. THIS RPT.	FUEL[a]	NO. OF BURNERS	OPERATION HRS/YR	NO_x EMISSIONS LB/HR AS NO_2			REHEAT, °C	REHEAT EMISSIONS, LB/HR		TOTAL NO_x EMISSIONS LB/HR	
						CURRENT LOAD		LOAD 100%		CURRENT LOAD	100% LOAD	CURRENT LOAD	100% LOAD
						%	NO_x						
REFINERY HEATER	65	A	R	24	7884	89	6.7	7.5	NONE[b]	N/A[c]	N/A	6.7	7.5
	93	B	R	72	8330	100	11.9	11.9	89	0.6	0.6	12.5	12.5
	115	C	R	12	7534	90	23.7	26.3	NONE[b]	N/A	N/A	23.7	26.3
	164	D	R	48	8235	88	34.0	38.6	22	0.22	0.25	34.2	38.8
	435	E	R	136	8059	80	71.2	89.0	NONE[b]	N/A	N/A	71.2	89.0
INDUSTRIAL BOILER	4	F	N	1	5944	100	0.4	0.4	128	0.04	0.04	4.4	4.4
	22	G	N	1	5843	52	1.9	3.6	78	0.1	0.2	2.0	3.8
	22	H	O	1	5843	52	5.5	10.6	78	0.1	0.2	5.5	10.8
	150	I	O	1	7884	48	9.4	19.6	68	0.3	0.7	19.9	20.3
	336	J	N	4	8376	54	36.9	68.3	83	1.1	2.1	38.0	70.4
CO BOILER	582	K	R	8	8400	45	181.1	402.4	NONE[b]	N/A	N/A	181.1	402.4
GLASS FURNACE	43	L	N	NAV[d]	8760	100	38.4	38.4	NONE[b]	N/A	N/A	38.4	38.4

[a]R = REFINERY GAS, N = NATURAL GAS, O = NO. 2 FUEL OIL

[b]REHEAT NOT REQUIRED

[c]NOT APPLICABLE

[d]NOT AVAILABLE

In addition to the three major control technologies considered in this study as applicable to refinery heaters, industrial furnaces and glass melting furnaces, it is recognized that a number of potentially other efficient alternative NO_x control strategies are applicable to glass melting furnaces. In many cases, these methods are likely to be implemented before post-combustion controls and would include process changes such as modifications to burner design, modification to excess air levels, and electric boosting. These process changes were not within the scope of the study and were therefore not included in the analysis.

1.3.1 Low NO_x Burners

Low NO_x burners (LNB) are widely used in Japan on utility and industrial boilers and on other industrial combustion equipment. The NO_x reduction is influenced by the burner configuration, size, type of fuel burned (oil, gas, coal, and fuel nitrogen content), and type of combustion modifications (CM) implemented prior to the use of LNB. For example, with one type of LNB burning heavy oil NO_x was reduced from 18 to 42% when operated without other CM techniques in use. When 40% reduction was achieved by other types of CM, such as flue gas recirculation (FGR), staged combustion, water injection, or a combination of these, further reductions of 10 to 20% were achieved by the addition of an LNB, for a total removal of 40 to 50% (Reference 1-1).

Recent U.S. and Japanese refinery experience indicates that certain low NO_x burners can reduce thermal NO_x emissions by 40% - 50% (References 1-1, 1-3). For gaseous fuels this results in an overall 40% - 50% reduction. In liquid fuels, because the fuel nitrogen component is virtually unaffected, the overall reduction rate is less.

1.3.2 Selective Noncatalytic Reduction

Ammonia reacts selectively with NO at approximately 1000°C (1830°F), forming N_2 and H_2O. As in the case of selective catalytic reduction SCR (described later), selective non-catalytic reduction (SNCR) requires the presence of a small amount of O_2 for the reaction to occur. Exxon Research and Engineering Company has patented the application of non-catalytic reduction as a NO_x control process, and is also referenced as Thermal $DeNO_x$.

Tests have been reported to show that the temperature interval, or "window", over which appreciable NO_x reduction occurs is approximately 100°C (180°F) and the reduction levels are a function of the NH_3 to NO_x mole ratio. The location of the temperature window which is nominally 1000°C can be lowered by the introduction of hydrogen. Depending on the amount of H_2 introduced (with H_2 to NH_3 ratios as high as 2), the reaction temperature is reduced by approximately 250°C (450°F).

Laboratory tests have shown that 80 to 90% NO_x reduction can be achieved with ammonia injection rates of 1.1 to 1.6 NH_3/NO_x mole ratios. However, for full-scale equipment applications, the removal rate appears to be limited to approximately 65%, with 50% being typical value for a constant load source and perhaps 40% for a source with a variable load (Reference 1-1). Temperature uniformity, NH_3 distribution and residence time at temperature are the key parameters affecting performance.

By-product emissions include unreacted ammonia. Concentrations in the exhaust stream resulting from the 1.5 NH_3/NO_x mole ratio required to achieve 50% reduction may be in the range of 30 to 50 ppm. The NH_3 has the potential for forming NH_4HSO_4 where SO_3 is present and condensing at temperatures of approximately 215°C (425°F) (Reference 1-1). Other emissions such as cyanides and nitrates have been reported, averaging 2 and 10 ppm, respectively (Reference 1-4). However, no correlation was reported between the amount of ammonia injected and the emission levels of these pollutants, thereby suggesting that the cyanide and nitrates may not be a by-product of the NH_3 injection process.

Full-scale use of SNCR has been applied in Japan, with approximately 11 units being reported, ranging from 190 to 1320 MMBtu/hr thermal input. These units include industrial and utility boilers, CO boilers, and crude oil heaters. Generally they are operated during pollution alerts only; two were demonstration units. A full-scale installation in the U.S. on a 50 MMBtu/hr oil field steam generator has been reported, with up to 65% removal at a mole ratio (NH_3/NO_x) of 1.5 (Reference 1-1). It has also been applied in the U.S. by KVB and Fletcher Oil, Carson, CA on refinery heaters. Details of the results and performance of the process are not currently available.

On the basis of the performance reported above for similar units, the feasibility for Thermal $DeNO_x$ achieving a 50% reduction has been shown for refinery heaters and steam boilers (References 1-1, 1-3).

Limitations on NO_x reduction exist with varying load conditions and multiple NH_3 injection grids may be required. To locate the NH_3 injection sites, a thorough thermal profile mapping of each NO_x source is required. Since this type of data normally does not exist for refinery heaters and industrial boilers, it was assumed for the equipment discussed in this report that suitable temperature profiles exist for placement of NH_3 injection grids in accessible locations.

1.3.3 Selective Catalytic Reduction (SCR)

The NO_x from stationary sources is virtually all nitric oxide (NO) and can be reduced to N_2 and H_2O by ammonia in the presence of certain base metal catalysts. In order to achieve a 90% reduction, temperatures in the range of 260 to 380°C (500 to 715°F) are required in the reactor with an NH_3 to NO_x ratio of 0.9 to 1.1 (References 1-1, 1-5). Small quantities of oxygen in amounts normally present in the emissions as a result of excess air (approximately 1%) in the combustion process are needed.

To determine the effect of NO_x removal rate on cost, SCR reactors in this study have been sized so that 50 to 90% NO_x removal can be achieved either alone or for use with other control options.

In some stationary sources, reheat of the exhaust gas is required to achieve the minimum effective temperature for optimum NO_x removal rates with catalysts currently in use. In those cases, recovery of a major fraction of the reheat energy can be effected through a heat exchanger downstream of the SCR unit thereby offsetting some of the fuel and capital cost penalties incurred with the reheating. It must be noted that this study was aimed at NO_x control and not energy conservation. Therefore, no attempt was made to include exhaust gas heat recovery equipment and credits to offset the cost of NO_x control in those specific equipments where gas temperatures were high enough for SCR and reheat was not required.

Criteria used for catalyst bed sizing are summarized in Table 1-2 and include type of fuel, flue gas temperature, SO_2 emissions, and particulate loading. In general, for a gas-fired unit under conditions of optimum flue gas temperature and negligible SO_2 and particulate emissions, a normal space velocity of approximately 6000 hr^{-1} (dry basis) could be considered. For cases in which sub-optimum temperatures are encountered either independently or in combination with SO_2 and particulate loading, a lower space velocity would be required as shown in Table 1-2. Oil-firing necessitates a lower space velocity due to associated SO_2 emissions and particulate loading. Flue gas temperatures for optimum catalyst performance were considered to be in the range of 350 to 400°C and the low operating temperatures are those between 255 and 260°C. As was noted above, tradeoffs between the cost of increasing the reheat temperature and the associated equipment and fuel costs versus the corresponding reduction in catalyst volume (increased space velocity) were not conducted.

1.3.4 Combinations of Control Technologies

In combining controls the cumulative effect of each control system is considered with no resultant degradation of individual system performance levels providing adequate space and appropriate conditions conducive to each system are available. Although space is assumed to be present, installation is not necessarily assumed to be without problems and some relocation of existing equipment may be needed. The combined control options that were considered are: LNB alone, SNCR alone, SCR alone, LNB with SNCR, LNB with SCR, SNCR with SCR, and LNB with SNCR plus SCR.

There does not appear to be any technical reason to preclude combining multiple NO_x control systems. However, cost considerations make some combinations unattractive. In addition, the overall complexity of the control system is increased by utilizing multiple systems.

1.4 Cost Estimates

A graphical representation of general NO_x removal cost-effectiveness trends for combined controls is presented in Figure 1-1. This report also presents the effect of load, fuel (gas versus oil) and reheat on control system cost-effectiveness.

TABLE 1-2

CATALYST BED SIZING CRITERIA AS RELATED TO REFINERY HEATER AND INDUSTRIAL BOILER EMISSION CHARACTERISTICS

FUEL	FLUE GAS CONDITIONS			SPACE VELOCITY,[d] NOMINAL (HR^{-1})	APPLICABLE EQUIPMENT, DESIGNATION[e]
	TEMP[a]	SO_2 [b]	PARTICULATES[c]		
GAS	OPTIMUM	NONE	NONE	6200	A
GAS	LOW[f]	NONE	NONE	4200	B, C, D, E, F, J
OIL	LOW	SOME	SOME	2400	H, I
GAS	LOW	SOME	SOME	2500	K

[a] OPTIMUM = 350 - 400°C
LOW = 255 - 260°C

[b] SOME = 5 - 200 ppm

[c] SOME = 0.01 - 0.3 GRAINS/STANDARD CUBIC FEET

[d] BIANNUAL CATALYST REPLACEMENT. SPACE VELOCITY IS ON A DRY BASIS

[e] DESIGNATION - THIS REPORT

[f] TEMPERATURE BASED ON MINIMIZING REHEATER AND HEAT RECOVERY EQUIPMENT AND FUEL REQUIREMENTS

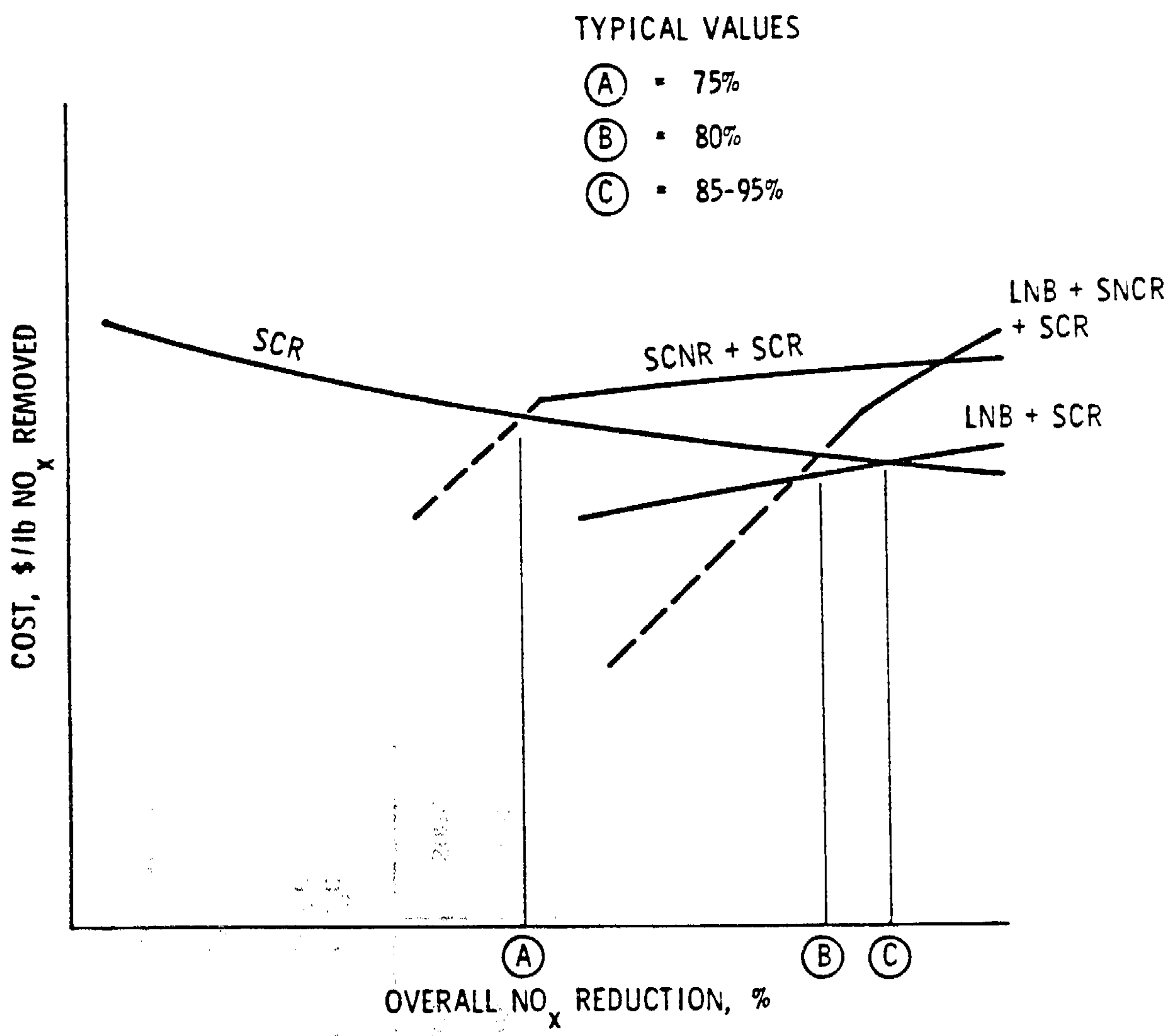

Figure 1-1 General NO_x Removal Cost-Effectiveness Trends as a Function of Overall NO_x Reduction

The costs reported do not reflect any tax savings that a company may incur from the installation of pollution control equipment such as investment tax credits, deduction for interest expense or depreciation. All of these factors would tend to reduce the net cost of the equipment to the company. Also the opportunity costs such as those resulting from lost production during retrofit shutdown were not included. This was considered a reasonable approach because the control equipment buildup was assumed to be incurring in parallel with normal equipment operation and installed or connected during normal maintenance shutdown periods. However, if operational schedules do not permit such an approach, lost production should be considered.

SCR is equivalent in cost to LNB plus SCR at points B and C, which correspond to overall NO_x removal rates. As an example, for reductions less than B, LNB plus SCR has a lower NO_x removal cost than any other combination or option. For reductions greater than C, SCR is the least costly option in terms of NO_x removal. It is apparent that SNCR plus SCR, and LNB plus SNCR plus SCR are not cost competitive.

Although an option may have a low NO_x removal cost, there may be other reasons which would make another slightly more costly alternative more desirable; i.e., there may be some advantage to combination LNB plus SCR for removal rates greater than C due to the capability of LNB to prevent total loss of NO_x control if the SCR system is taken off the line for catalyst replacement or for other reasons.

An average cost index of combined NO_x control systems relative to SCR (alone) at 90% reduction is shown in Figures 1-2 and 1-3 for refinery heaters and industrial boilers. The combinations of systems that achieve specific control levels are shown.

In the 80-90% range, the combination of LNB plus SCR is comparable to the cost of SCR installations (Table 1-5). For less than 80%, other combinations or individual controls are less costly than an equivalent sized SCR reactor.

In general, NO_x control on boilers is more cost-effective relative to SCR than heaters (Figure 1-2). Also, larger units are more cost-effective than smaller units (Figure 1-3).

The effects of reheat and reheat recovery on costs for industrial boilers are illustrated in Figure 1-4 ($/lb vs. size). Heaters are less consistent in terms of cost-effectiveness as a function of size.

Table 1-3 depicts the cost of NO_x reduction with the use of low NO_x burners at 100% load. All costs are given in 1981 dollars. Total quantities of NO_x removed, capital cost, annual cost, and cost-effectiveness in terms of dollars per pound of NO_x removed and dollars per million Btu's are presented. These costs are based on an estimated 40% NO_x removal rate of the low NO_x burners relative to conventional burners. In the case of the 22 MMBtu/hr industrial boiler which fires either natural gas or No. 2 fuel oil and the 150 MMBtu/hr Boiler which burns oil, it was estimated that the LNB would cause a 40% reduction

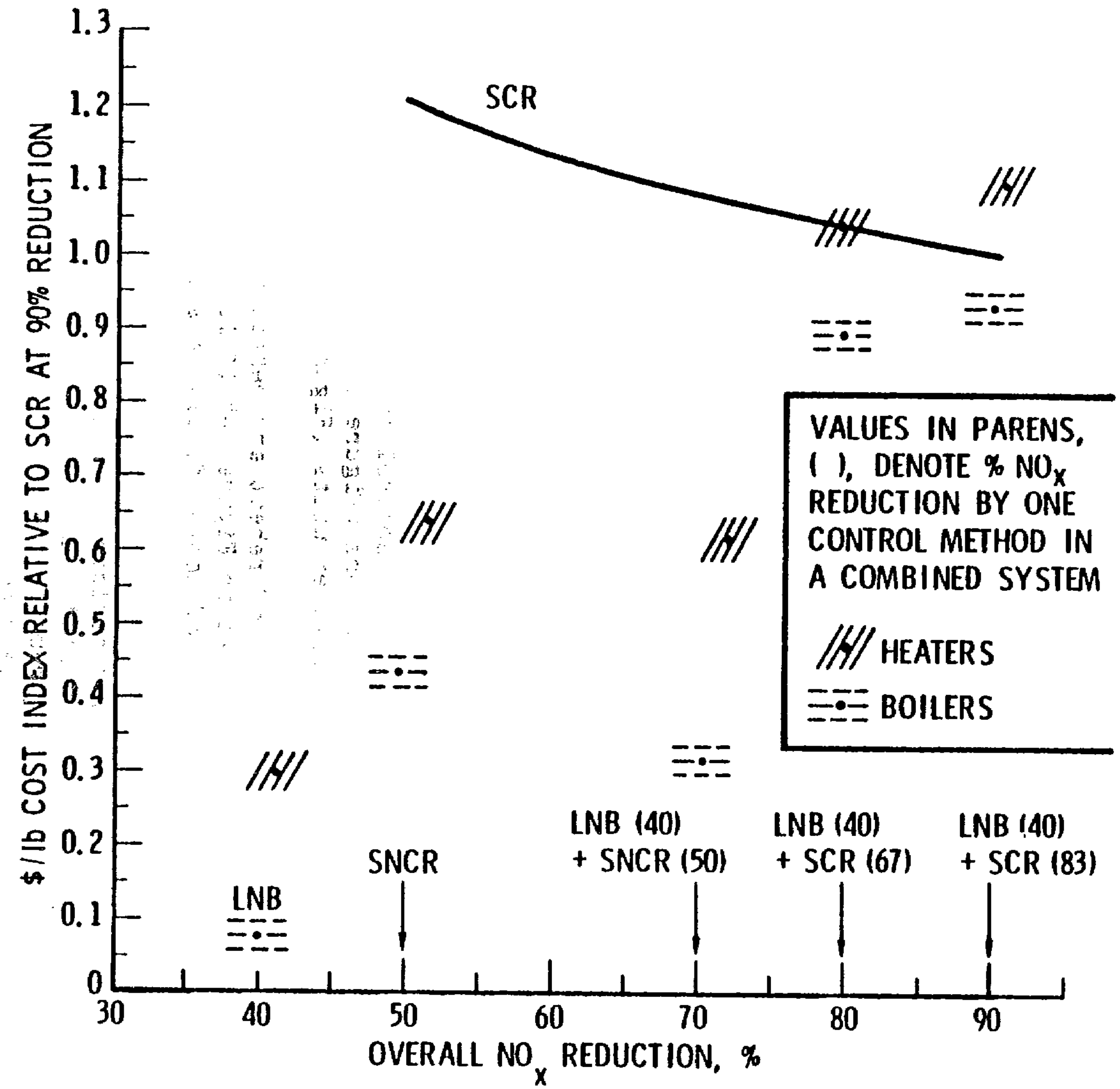

Figure 1-2 Relative Cost of NO_x Removal as a Function of Overall Reduction for Heaters and Boilers Employing Various Combinations of Controls

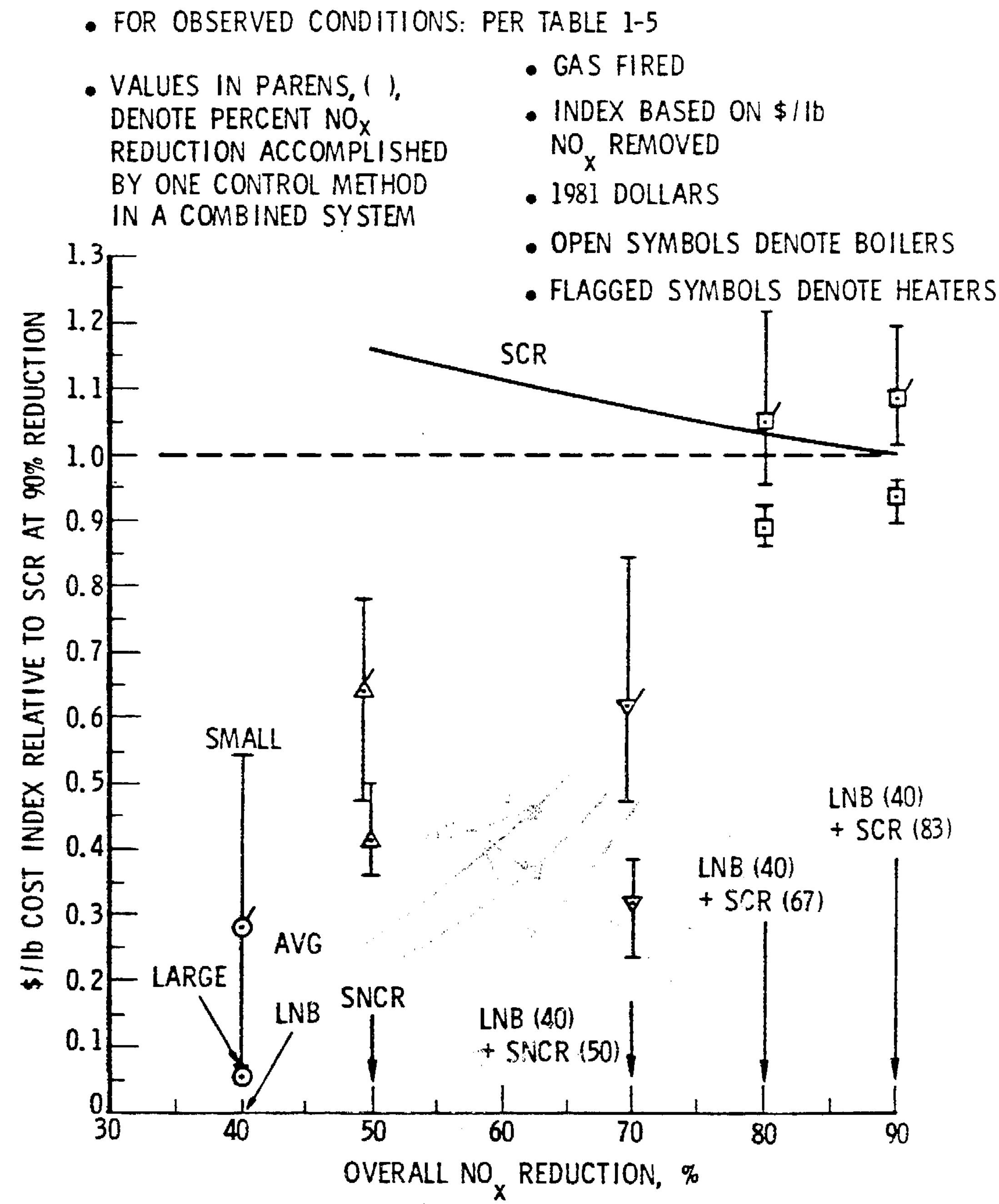

Figure 1-3 Cost of Control Indexed to SCR at 90% Reduction for Combinations of Controls

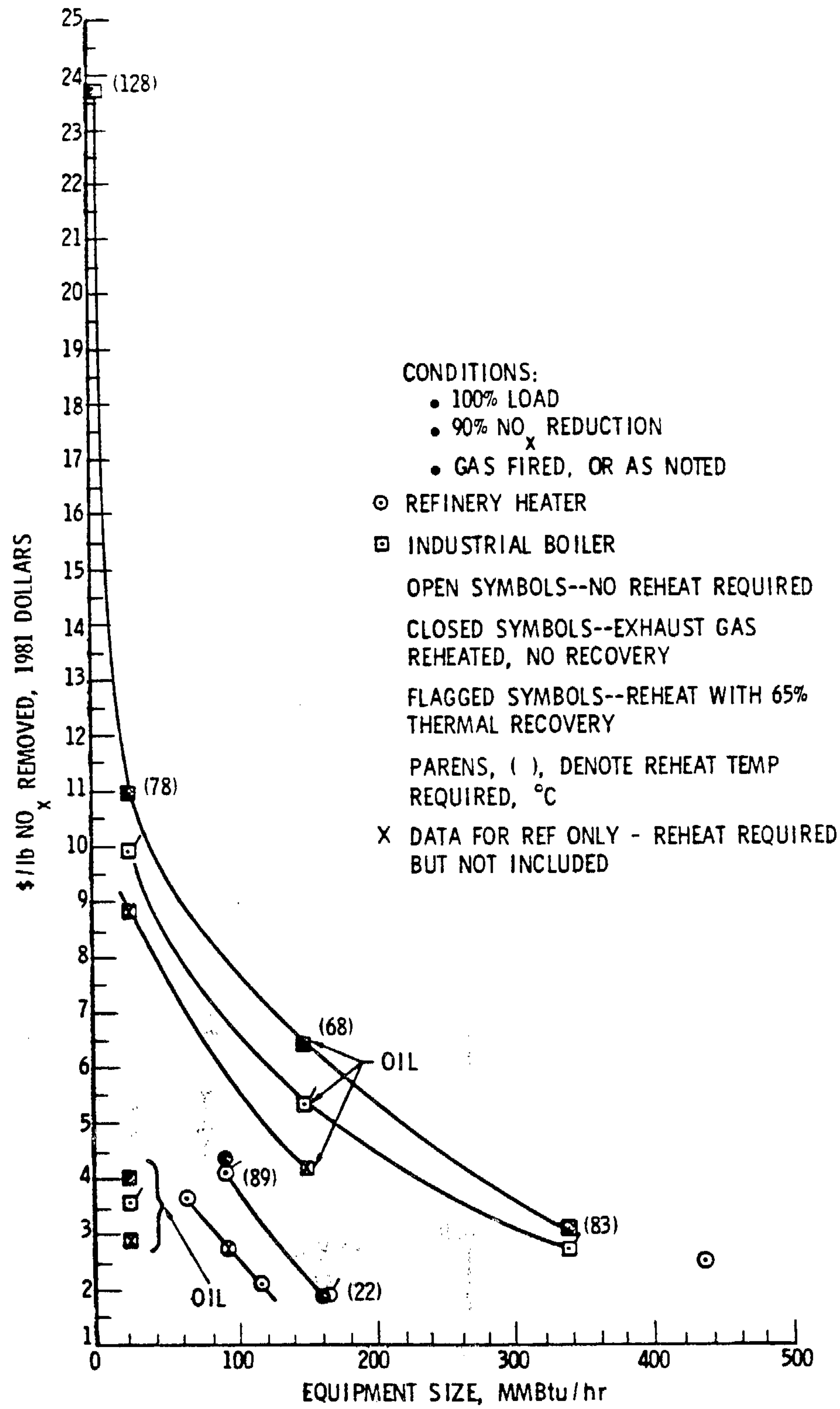

Figure 1-4 Cost of NO_x Removal Using SCR on Refinery Heaters and Industrial Boilers (1981 Dollars)

TABLE 1-3

COST OF NO_x REDUCTION WITH USE OF LOW NO_x BURNERS WITH GASEOUS FUELS AT 100% LOAD (1981 DOLLARS)

EQUIPMENT	UNIT DESIG	SIZE MMBTU/HR	HRS/YR OPERATED	NO_x EMISSIONS LB/YR	BURNERS QTY	BURNERS CAPITAL COST, $[a]	BURNERS TOTAL CAPITAL INVESTMENT, $	NO_x[b] REMOVED LB/HR	ANNUAL COST, $	$/LB NO_x	$/ MMBTU
REFINERY HEATER	A	65	7884	7.5	24	108,400	145,400	3.0	46,500	1.97	0.091
	B	93	8330	11.9	72	148,600	199,200	4.8	63,800	1.60	0.082
	C	115	7534	26.3	12	28,700	38,500	10.5	12,300	0.16	0.014
	D	164	8235	38.6	48	100,200	134,400	15.4	43,000	0.34	0.032
	E	435	8059	89.0	136	280,500	376,100	35.6	120,400	0.42	0.034
INDUSTRIAL BOILER	F	4	5944	0.40	1	2,900	3,900	0.16	1,240	1.30	0.052
	G	22	5843	3.6	1	8,200	10,900	1.5	3,500	0.40	0.027
	H	22[c]	5843	10.6	1	8,200	10,900	1.0[d]	3,500	0.61	0.027
	I	150[c]	7884	19.6	1	18,200	24,400	3.5[d]	7,800	0.28	0.006
	J	336	8376	68.3	4	63,600	85,200	27.3	27,300	0.12	0.010
CO BOILER	K	582	8400	402.4	8	150,200	161,000	161.0	51,600	0.038	0.033

[a] INCLUDING 72% RETROFIT FACTOR

[b] ESTIMATED 40% NO_x REMOVAL (THERMAL NO_x) RELATIVE TO EXISTING CONVENTIONAL BURNERS

[c] NO. 2 FUEL OIL

[d] EST. 40% THERMAL NO_x REDUCTION. EST. 55% FUEL NO_x NOT AFFECTED

in thermal NO_x emissions while leaving the estimated 55% fuel NO_x in the emissions unaffected. Cost-effectiveness of low NO_x burners ranges from \$0.16-1.97/lb NO_x removed for heaters, \$0.12-1.30/lb NO_x removed for boilers and \$0.38/lb NO_x removed for the CO boilers. In general, the higher cost applies to the smallest units and the lower costs to the larger installations.

The cost for SCR installations is summarized in Table 1-4 and it is based on a 90% NO_x removal rate, also at 100% load. In addition, where exhaust gas reheat is necessary to meet catalyst temperature requirements, and can be effectively recovered (based on a 65% thermal recovery), the credit from reheat recovery is shown in the column following the amount of reheat required. A credit averaging about \$0.80/lb NO_x for units requiring about 80°C of reheat is shown. Also, the simple payback period for heat recovery equipment is presented.

The range of costs for 90% SCR control is \$1.95-3.95/lb NO_x removed for heaters and \$3.68-23.75/lb NO_x removed for boilers. In general, the lower costs apply to the larger installations. The cost for the CO boiler is \$3.60/lb, and for a 200 TPD flint glass melting furnace is \$1.45/lb NO_x.

Table 1-5 summarizes the cost of combined NO_x control systems (including SNCR alone). Values are computed on the basis of observed operating load (at the time of the study) which varies for each unit, and costs depend on levels of secondary controls as indicated. The cost of SCR (alone) at the corresponding control level is also shown for comparison. The data support the information discussed earlier and presented in Figures 1-2 and 1-3 regarding the costs of various methods and combinations relative to SCR.

Table 1-6 which is cross-indexed to Figure 1-1, compares the cost-effectiveness of combined control systems with SCR at observed operating loads.

The performance matrix represented in Table 1-7 summarizes the previous tables and graphs and shows the degree to which each control option can be cost-effectively utilized for the various installations examined.

TABLE 1-4 COST OF SCR INSTALLATIONS FOR NO_x CONTROL

EQUIPMENT	SIZE	UNIT DES.	SCR 90% NO_x REMOVAL, 100% LOAD, 1981 DOLLARS[a]						TOTAL[f] EMISSIONS W/O CONTROLS	REHEAT °C	SAVINGS FROM REHEAT REC., $/lb	HEAT REC. SIMPLE PAYBACK PERIOD, YR
			CAP COST, $	CAP INV., $	RETROFIT FACTOR, %		$/lb[b]	$/MMBtu[b]				
					THIS REPORT	OTHER[e]						
REFINERY HEATER	65	A	322,100	480,500	15	23	3.65	0.38	7.5	NONE	N/A	N/A
	93	B	595,300	892,000	15	103	4.22	0.51	12.5	89	0.16	2.1
	115	C	544,300	815,900	15	27	2.08	0.43	26.3	NONE	N/A	N/A
	164	D	793,400	1,193,900	15	36	1.92	0.42	38.8	22	0.01	2.1
	435	E	1,806,600	1,655,600	15	12	2.66	0.49	89.0	NONE	N/A	N/A
INDUSTRIAL BOILER	4	F	103,300	153,900	15	55	23.75	2.35	0.44	128	NO	>8
	22	G	322,100[d]	451,000	15	70	9.86	1.54	3.8	78	1.07	4.8
	22	H[c]	322,100	451,000	15	70	3.59	1.57	10.8	78	0.43	4.8
	150	I[c]	1,025,300	1,542,700	15	59	5.32	0.65	20.3	68	1.25	1.0
	336	J	1,752,700	2,630,400	15	20	2.69	0.51	70.4	83	0.34	1.7
CO BOILER	582	K	6,137,300	9,256,000	15	18	1.69	1.05	402.4	NONE	N/A	N/A

[a] 100% LOAD FOR THE ANNUAL OPERATING HOURS SHOWN IN TABLE 1-3

[b] WITH REHEAT AND 65% REHEAT RECOVERY

[c] NO. 2 FUEL OIL

[d] DESIGNED FOR FUEL OIL OPERATION

[e] SEE PARAGRAPH 2.2.1, EQUIVALENT TO 15% USED IN THIS REPORT

[f] INCLUDING NO_x FROM REHEAT

TABLE 1-5 COST OF COMBINED NO_x CONTROL SYSTEMS

(1981 DOLLARS)

EQUIPMENT	DESIG	SIZE, MMBTU/HR	LOAD, %	REHEAT[a]/ RECOVERY	SNCR[b]		SCR	LNB(40)+ SNCR(50)[f]		SCR	LNB(40)+ SCR (67)		SCR	LNB(40)+ SCR (83)		SCR	HOURS/ YR
					%	$/lb	$/lb	%	$/lb	$/lb	%	$/lb	$/lb	%	$/lb	$/lb	
REFINERY HEATER	A	65	89	NOT REQ.	50	3.10	5.10	70	3.50	4.40	80	5.00	4.20	90	4.90	4.10	7881
	B	93	100	89°C/NO	50	2.20	5.40	70	2.50	4.90	80	4.90	4.70	90	5.00	4.60	8330
			72	89°C/NO	50	2.10	6.50	70	2.50	5.90	80	5.90	5.70	90	6.00	5.60	8330
	C	115	90	NOT REQ.	50	1.80	2.90	70	1.40	2.50	80	2.20	2.40	90	2.30	2.30	7534
	D	164	88	22°C/NO	50	1.50	2.70	70	1.30	2.40	80	2.30	2.30	90	2.40	2.20	8235
	E	435	80	NOT REQ.	50	1.40	2.90	70	1.30	2.80	80	2.60	3.00	90	2.80	2.70	8059
INDUSTRIAL BOILER	F	4	100	128°C/NO	50	13.00	>30	70	10.20	28.50	80	22.50	27.25	90	23.50	26.00	5944
	G	22	52	78°C/NO	50	6.90	18.50	70	5.40	17.30	80	14.50	16.75	90	14.80	16.00	5843
	H	22[e]	52	78°C/NO	50	2.60	7.00	70	---	6.20	80	5.80	6.00	90	5.70	5.80	5843
	I	150[e]	100	68°C/65%	50	1.85	6.50	70	---	5.80	80	5.50	5.60	90	5.10	5.30	7884
	J	336	54	83°C/NO	50	1.60	4.60	70	1.40	4.50	80	3.90	4.90	90	4.20	4.50	8376
CO BOILER	K	582	45	NOT REQ.	50	0.86	4.50	70	0.67	3.90	80	3.70	3.70	90	3.50	3.40	8400
GLASS FURNACE	L	43	100	NOT REQ.	50	0.90	1.90	N/A[c]	N/A	N/A	80[d]	1.84	1.50	90	1.85	1.46	8760

[a] NO. REHEAT REQUIRED FOR SNCR & LNB. REHEAT REQD ONLY FOR SCR AS INDICATED.

[b] APPLICABILITY MUST BE DETERMINED BY TEST. THE PRESENCE OF APPROPRIATE CONDITIONS FOR USE OF SNCR MUST BE DETERMINED EXPERIMENTLY.

[c] CONSIDERED NOT APPLICABLE BECAUSE OF THE UNCERTAINTY OF THE SUITABILITY OF LOW NO_x BURNERS.

[d] 50% SNCR & 60% SCR

[e] NO. 2 FOR FUEL OIL; ALL OTHERS GASEOUS FUEL

[f] THE VALUES IN PARENS () DENOTE THE PERCENT NO_x REMOVED BY THE CORRESPONDING CONTROL MEASURE

TABLE 1-6

COMPARISON OF COMBINED NO_x CONTROL SYSTEMS WITH SCR

EQUIPMENT	UNIT DESIG	SIZE, MMBTU/HR	OPERATING LOAD, %	CROSS-OVER RELATIVE TO SCR[a]					
				SNCR + SCR (A)[b]		LNB + SNCR + SCR (B)		LNB + SCR (C)	
				%	$/LB	%	$/LB	%	$/LB
REFINERY HEATER	A	65	89	65	4.60	75	4.20	65	4.60
	B	93	100[c]	75	4.70	80	4.60	75	4.80
		93	72[c]	70	5.90	80	5.70	70	6.00
	C	115	90	65	2.60	80	2.40	90	2.30
	D	164	88[c]	65	2.40	80	2.20	80	2.20
	E	435	80	75	2.90	85	2.80	90	2.80
INDUSTRIAL BOILER	F	4	100	75	25.00	90	26.00	>100	23.00
	G	22	52[c]	75	17.00	90	16.50	95	15.70
	H	22[d]	52[c]	75	6.20	60	6.10	90	5.70
	I	150[d]	100[c]	75	5.70	80	5.40	100	5.20
	J	336	54[c]	80	4.50	90	4.50	95	4.40
CO BOILER	K	582	45	80	3.70	90	3.50	95	3.40

a Rates at which cost of Combination Controls begin to exceed SCR, See Fig 1-1
b Ref Fig 1-1
c With Reheat
d Fuel Oil

TABLE 1-7. SUMMARY OF POTENTIAL COST EFFECTIVE NO_x REDUCTION LEVELS USING SINGLE AND MULTIPLE NO_x CONTROL METHODS

UNIT DESIGN	SIZE \ CONTROL OPTION	LNB	SNCR	SCR	LNB + SNCR	LNB + SCR	SNCR + SCR	LNB + SNCR + SCR
	REFINERY HEATERS							
A	65 MMBtu/Hr	40[a]	50	70-90	70	X[b]	X	X
B	93 MMBtu/Hr	40	50	70-90	70	70-80	80	X
C	115 MMBtu/Hr	40	50	80-90	70	70-90	X	X
D	164 MMBtu/Hr	40	50	80-90	70	70-90	X	X
E	435 MMBtu/Hr	40	50	80-90	70	70-90	X	85
	INDUSTRIAL BOILERS							
F	4 MMBtu/Hr	40	50	X	70	70-90	X	X
G	22 MMBtu/Hr (gas)	40	50	X	70	70-90	X	X
H	22 MMBtu/Hr (oil)	18	50	80-90	60	60-90	X	X
I	150 MMBtu/Hr (oil)	18	50	60-90	60	60-90	X	80-85
J	336 MMBtu/Hr	40	50	90	70	70-90	X	85-90
K	582 MMBtu/Hr CO Boiler	40	50	85-90	70	70-90	X	85-90
L	Glass Furnace, 200 TPD	N/A[c]	50	50-90	N/A	N/A	X	N/A

[a] Overall NO_x Reduction, %

[b] X Denotes Other Methods are Less Costly to Achieve Designated Control Levels

[c] N/A Denotes the Method to be Not Applicable for Technical or Operational Reasons

1.5 Findings

The results of this study have shown that certain combinations of NO_x control systems are reasonable from a cost perspective; however, limitations may exist in utilizing a combination approach involving the increased complexity of operating more than one system. For example, physical and operational integration of separate control and instrumentation systems is necessary for the optimum combination of any of the technologies. Consequently, it is recommended that problems of this nature be quantitatively assessed in future pilot/test programs. Significant findings from this study are:

(1) For each control option and type of units examined in this study, the cost of NO_x control is affected by the type of emission source, capacity factor, fuel burned, necessity for flue gas reheat, and retrofit considerations. Thus, a typical cost for NO_x removal in terms of \$/lb NO_x cannot be established.

(2) In general, NO_x control costs for refinery heaters are less in terms of \$/lb NO_x removed than industrial boilers.

(3) NO_x control installations on larger refinery heaters or industrial boilers are generally more cost-effective than smaller units.

(4) Refinery heaters and industrial boilers that require flue gas reheat for optimal SCR performance are costlier than those units not requiring reheat; however, the reheat cost can be offset to a significant extent by reheat recovery.

(5) In general, combinations of controls, primarily low NO_x burners and SCR, are cost competitive with SCR (alone) between 80 and 90% NO_x removal levels for both heaters and boilers.

(6) On the average, certain combinations of controls are less costly than SCR at NO_x removal levels in the range of approximately 60 to 70%; the cost of the combined system representing approximately 38% of SCR costs at comparable removal levels.

(7) At 50% NO_x removal, SNCR has the lowest removal cost, and at 40%, LNB is least costly; approximately 11% of the cost for 90% removal.

1.6 References

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